PROCEEDINGS, Thirty-Eighth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 11-13, 2013
SGP-TR-198

COMPARISON OF GEOTHERMAL WITH SOLAR AND WIND POWER GENERATION SYSTEMS

Kewen Li

China University of Geosciences, Beijing/Stanford University
Stanford Geothermal Program
Stanford, CA94305, USA
e-mail: kewenli@stanford.edu

ABSTRACT

Geothermal, solar and wind are all clean, renewable energies with a huge mount of resources and a great potential of electricity generation. The unfortunate fact is that the total capacity installed of geothermal electricity is left behind solar and wind. In this paper, attempt has been made to find the essential reasons to cause the above problem and to look for the solutions. Cost, payback time, size of power generation, construction time, resource capacity, characteristics of resource, and other factors were used to compare geothermal, solar, and wind power generation systems. Furthermore, historical data from geothermal, solar, and wind industries were collected and analyzed. Suggestions have been proposed for geothermal industry to catch up solar and wind industries.

INTRODUCTION

Renewable energy sources have grown to supply an estimated 16.7% of the total global energy consumption in 2010. Of this total, modern renewable energy (wind, solar, geothermal, etc.) accounted for an estimated 8.2%, a share that has increased in recent years (Renewables 2012: Global Status Report).

It is known that geothermal energy has many advantages compared with solar and wind systems. These advantages include weather proof, base load, great stability, and high thermal efficiency. The total installed capacity of geothermal electricity, however, is much less than solar and wind. The power of the total solar PVs manufactured by China in the last five years were equal to the total geothermal power installed in the entire world in the last one hundred years.

As summarized in Renewables 2012: Global Status Report, renewables accounted for almost half of the estimated 208 gigawatts (GW) of electric capacity added globally during 2011. Wind and solar photovoltaics (PV) accounted for almost 40% and 30% of new renewable capacity, respectively, followed by hydro-power (nearly 25%). By the end of 2011, total renewable power capacity worldwide exceeded 1,360 GW, up 8% over 2010; renewables comprised more than 25% of total global power-generating capacity (estimated at 5,360 GW in 2011) and supplied an estimated 20.3% of global electricity. Non-hydropower renewables exceeded 390 GW, a 24% capacity increase over 2010. Unfortunately, the contribution of geothermal power is very small.

Not only do future energy technologies need to be clean and renewable, but they also need to be robust, especially in some developing countries such as China. Recently the heavy fog enveloped a large swathe of East and Central China was an example. There was neither sunshine (no solar energy) nor wind (no wind turbine rotating). Beijing was hit 4 times by heavy haze and fog within one month in January 2013. Hundreds of flights were cancelled and highways were closed. Beijing meteorological observatory issued a yellow alert (the highest level alert) for heavy fog on January 22, 2013.

In this study, cost, payback time, capacity factor, size of power generation, construction time, resource capacity, characteristics of resource, social impact, and other factors were compared for geothermal, solar, and wind power generation systems. Historical data from geothermal, solar, and wind industries were collected and analyzed. Possible directions have been proposed to speed up geothermal power growth. Note that only geothermal electricity generation was considered and direct use of geothermal energy was not included in this paper.

COMPARISON OF RESOURCES, INSTALLED POWER AND CAPACITY INCREASE

The resources, installed capacity, and its increase in the last three years for PV, wind, hydro and geothermal energies are listed in Table 1. Note that the resources of the four energy types from different references are very different. According to GEA, the total geothermal power installed in world was about 11.2 GW until May 2012 (also see Clean Energy, v.6, p. 72, 2013). According to WEA (2000), geothermal has the largest resources among the four types of renewable energies.

Table 1: Comparison of Resources, installed power and increase in last three years (2009-2011).

Energy	Resource (TW)	Resource (TW)	Installed (GW)	Increase (GW)
PV	6500①	49.9⑥	70③	47.0③
Wind	1700①	20.3	240③	79.0③
Hydro	15955④	1.6	970③(1010)⑤	55.0③
Geoth	67⑦	158.5	11.2	0.30

①Jacobson (2009)
②Chamorro, et al. (2012)
③REN21 Report (2012)
④Kenny, et al. (2010)
⑤Lucky (2012)
⑥WEA (2000)
⑦Stefansson (2005)

Figure 1 shows the modeled world wind speeds at 100 meter. The resource of all wind worldwide was about 1700 TW and that over land in high-wind areas outside Antarctica was about 70-170 TW reported by Jacobson (2009). Note that the predicted world power demand in 2030 would be 16.9 TW.

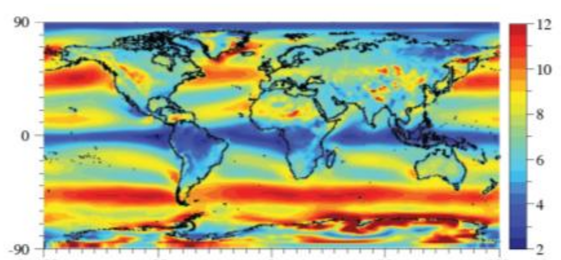


Figure 1: Modeled world Wind speeds at 100 meter.

The modeled solar downward radiation in the world is shown in Figure 2. The global average radiation was about 193 W/m^2 and that over land was around 185 W/m^2. The resource of all PV worldwide was about 6500 TW and that over land in high-solar locations was about 340 TW, as reported by Jacobson (2009).

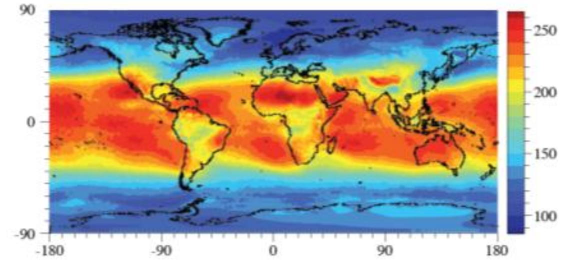
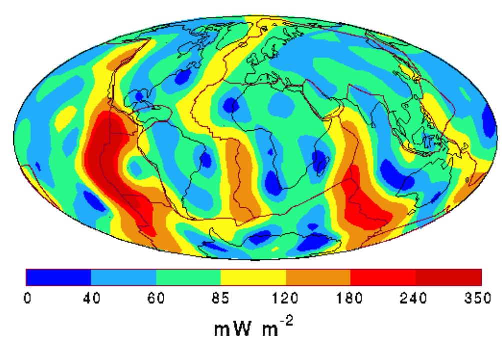


Figure 2: Modeled world Surface radiation (W/m^2) (global average: 193; land: 185)

Figure 3 shows the distribution of world average heat flow rate (Figure 3a) and the location of world geothermal power plants (Figure 3b). One can see that the two maps match very well, that is, the areas with the highest heat flow rates have the most geothermal power plants. The geothermal resource worldwide was about 67 TW (Stefansson, 2005).

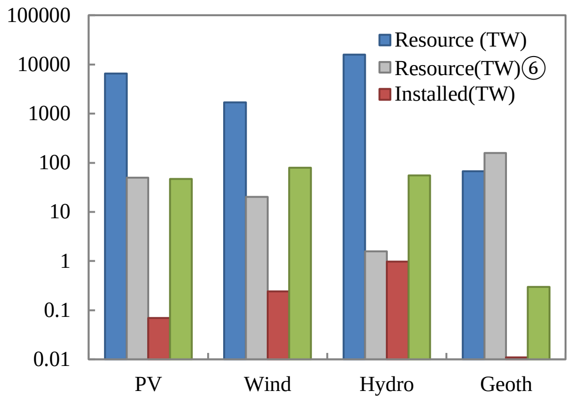


(a) Distribution of world heat flow rate (http://geophysics.ou.edu/geomechanics/notes/heatflow/global_heat_flow.htm) average: 0.06 W/m^2

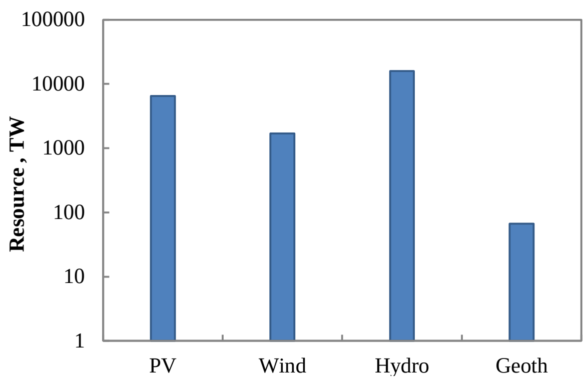
(b) Location of world geothermal power plants (source: thinkgeoenergy.com)

Figure 3: Distribution of world heat flow rate and geothermal power plants.

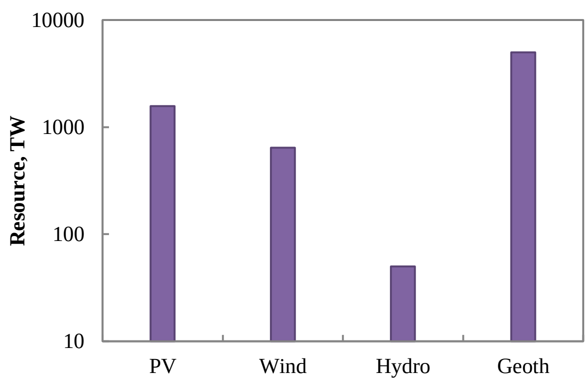
The comparison of resources, installed capacity and the increase of power in the last three year is plotted in Figure 4.



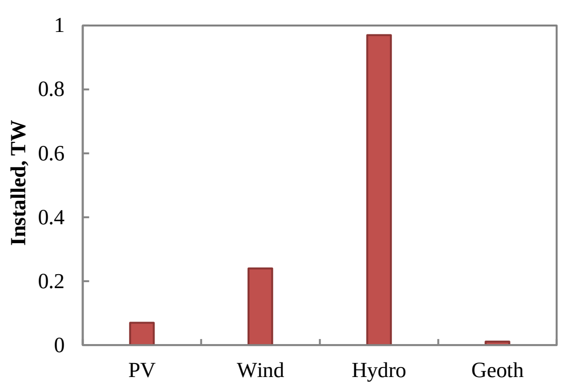
(a) Resource, installed power and increase



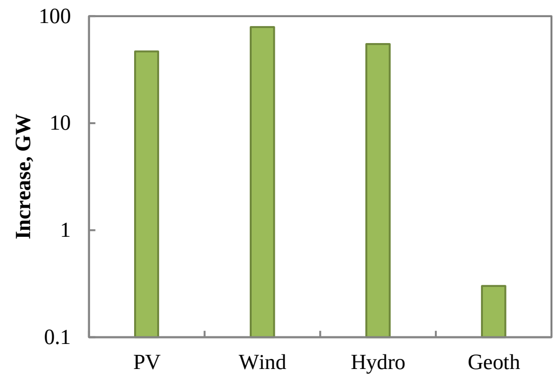
(b) Resource (Jacobson , 2009)



(c) Resource (WEA)



(d) installed power



(e) power increase in last three years

Figure 4: Resources, installed capacity and the increase in the last three years.

The change of the installed global power capacity with time for geothermal, PV, and wind is shown in Figure 5. One can see that PV's power change rate was the maximum, followed by wind power. The above trend can also be seen in Figure 6, which demonstrates the average annual growth rates of renewable energy capacity during the period of 2006–2011.

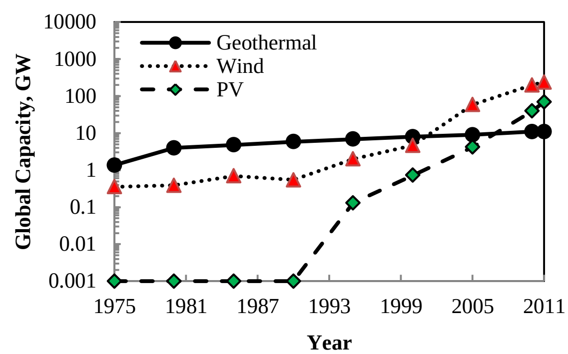


Figure 5: Comparison of installed global capacity for individual energy types.

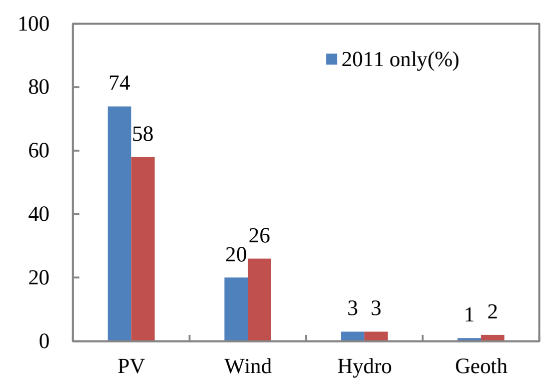


Figure 6: Average annual growth rates of renewable energy capacity, 2006–2011 (REN 21, 2012).

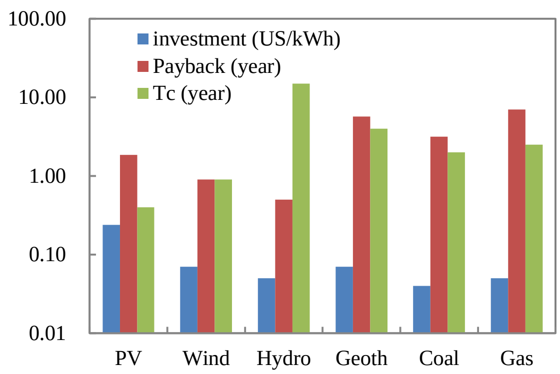
Note that the average annual growth rate of geothermal power was about 2% while that of PV was about 58% during the same period and up to 74% in 2011 only.

COMPARISON OF COST, EFFICIENCY, AND ENVIRONMENTAL IMPACTS

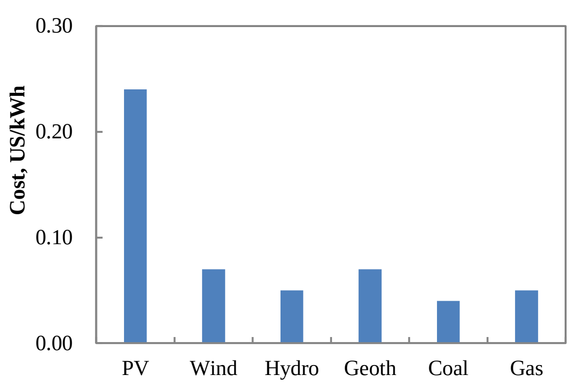
The cost, payback time, and construction time for different energy types are listed in Table 2. The data are also plotted in Figure 7. The cost of geothermal energy is very close to wind energy but much less than PV. Compared with wind and PV, the main disadvantages of geothermal energy may be the long payback time and the construction period (Tc).

Table 2: Comparison of cost, payback time, and construction period (Kenny, et al., 2010)

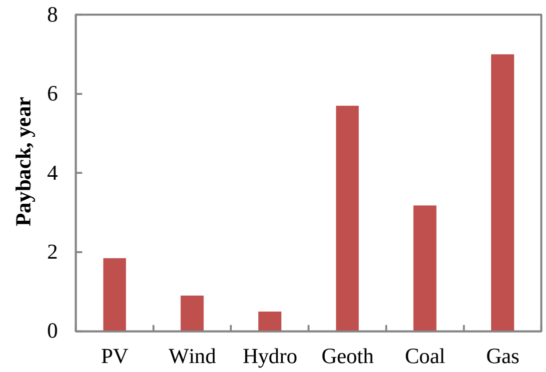
	Cost (US/kWh)	Payback (year)	Construction (year)
PV	$0.24	1-2.7	0.3~0.5
Wind	$0.07	0.4-1.4	<1
Hydro	$0.05	11.8(small)	1
		0.5 (large)	10~20
Geoth	$0.07	5.7	3~5
Coal	$0.04	3.18	1~3
Gas	$0.05	7	2~3



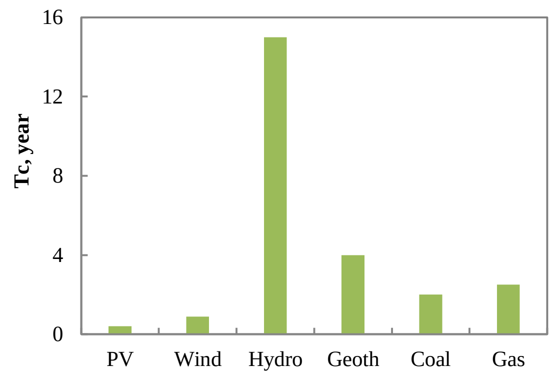
(a) All financial



(b) cost



(c) payback time



(d) construction period

Figure 7: Comparison of cost, initial investment, payback time, and construction period.

In addition to cost, parameters like capacity factor (CF), efficiency, and environmental impacts for individual energy generation technology are also important factors that affect the growth. These parameters are listed in Table 3 and plotted in Figure 8.

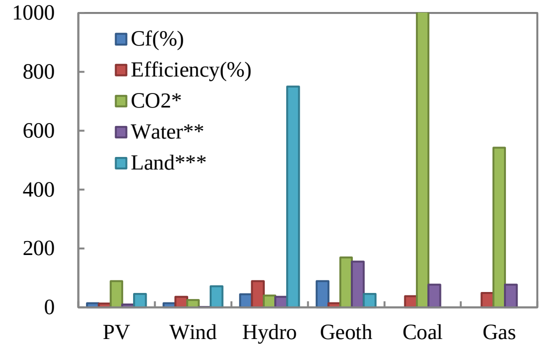
Table 3: capacity factor, efficiency, and environmental impacts (Evan, 2009)

	CF(%)	Efficiency(%)	$CO_2$①	Water②	Land③
PV	8-20	4-22	90	10	28-64
Wind	20-30	24-54	25	1	72
Hydro	20-70	>90	41	36	750
Geoth	90+	10-20	170	12-300	18-74
Coal		32-45	1004	78	
Gas		45-53	543	78	

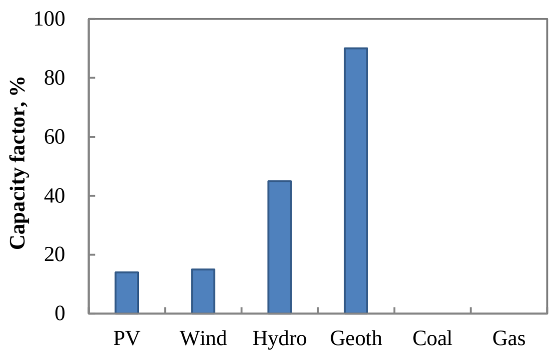
① Average greenhouse gas emissions expressed as CO_2 equivalent for individual energy generation technologies: CO_2 equivalent g/kWh

② Water consumption in kg/kWh of electricity generation

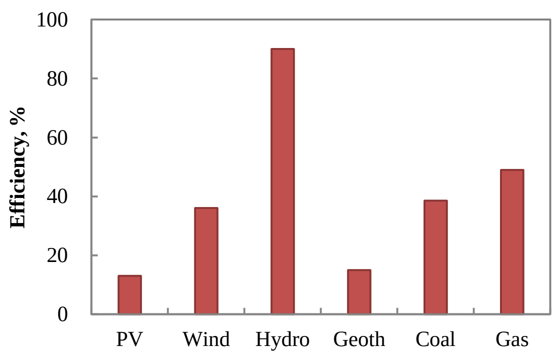
③ Units: km^2/TWh



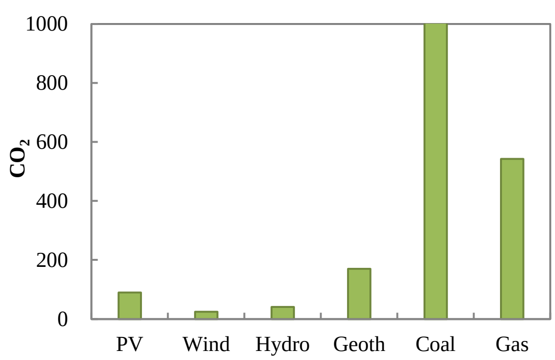
(a) All financial



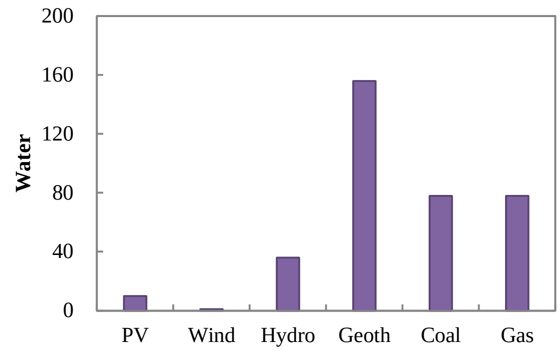
(b) Capacity factor



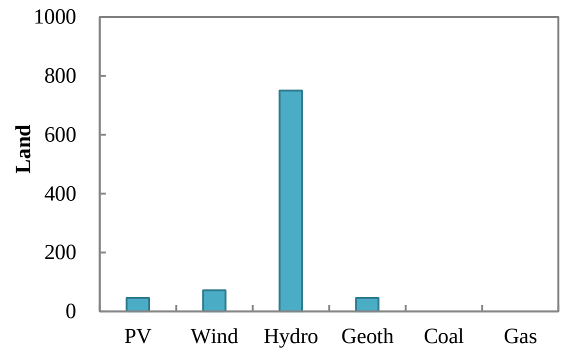
(c) Efficiency



(d) CO_2: g /kWh



(e) Water: kg/kWh of electricity generation



(f) Land: in the units of km^2/TWh

Figure 8: capacity factor, efficiency, and environmental impacts

Geothermal power has the highest capacity factor, over 90% in many cases, as listed in Table 3. The average value of the capacity factor of PV is about 14% and that of wind is around 25%. Considering this, the energy generated per year may be more important than the power installed. The amount of energy generated per year was calculated using the power installed listed in Table 1 and the capacity factor from Table 3 and the results are plotted in Figure 9. The energy generated by geothermal was more or close to PV after considering the capacity factor.

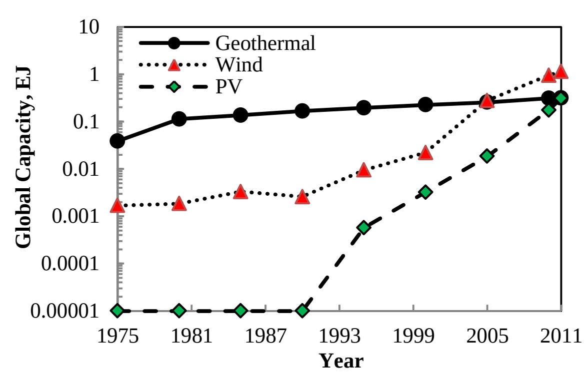


Figure 9: Comparison of generated energy for individual energy type.

One can see from Table 3 that the renewable energies all have the problem of significant footprint (Figures 10-12), occupying a large amount of land.

Figure 10: Solar footprints (cncmrn.com/channels/energy/20100929/365527.html)

Figure 11: Wind footprints (afdata.cn/html/hygz/nyky/20090730/8420.html;ewindpower.cn/news/show-htm-itemid-2482.html)

Figure 12: Geothermal footprints. (hb114.cc/news/hydt/20090807103400.htm)

Geothermal power has the largest consumption of water because of the need of cooling. However the water consumption by geothermal power could be reduced remarkably by using new cooling technologies.

COMPARISON OF SOCIAL IMPACTS AND GOVERNMENT BARRIERS

Social impact of renewable energies is also an important factor to affect the growth rate, even the existence in some areas or communities. Table 4 lists the social impacts (Evans, et al., 2009) and the government barriers (mostly the infrastructure system). Relatively, PV and wind have minor social impacts. The main social impact of geothermal may be seismic events, which could be very serious in some cases (Majer, et al., 2008). Except hydro-power, the other renewable energies may all face the problem of integrating and improving the grid and other infrastructure systems.

Table 4: Qualitative social impact assessment

Energy	Impact	Gov. Barriers
PV	Toxins: Minor-major	Infrastructure (grid) need to be improved
	Visual: Minor	
Wind	Bird strike: Minor	Infrastructure (grid) need to be improved
	Noise: Minor	
	Visual: Minor	
Hydro	Displacement: Minor-major	No barriers and grid problem
	Agricultural: Minor-major	
	River Damage: Minor-major	
Geothermal	Seismic: Minor-major	Infrastructure (grid) depends on location
	Odour: Minor	
	Pollution: Minor-major	
	Noise: Minor	

UNIT POWER SIZE AND MODULARIZATION

Do the size of a power unit and the ability of modularization affect the growth of a renewable energy? It is difficult to answer for the power unit size but the answer to the effect of modularization is yes. The possible, commercially available minimum unit power size, the ability of modularization, and the scalability of the individual renewable energy are listed in Table 5. Also demonstrated in Table 5 is the difficulty to assess the resources of renewable energies. It is known that PV power is highly modularized, followed by wind power. PV also has the smallest commercially available minimum power units. Note that PV power had an annual growth rate of 74% in 2011 only (REN21, 2012). On the other hand, geothermal has the largest commercially available minimum power units. Geothermal power had a less than 1% growth rate in 2011, only 2% in a five-year period from end-2006 to 2011 (REN21, 2012). It is difficult for geothermal power to be modularized. The fact is that almost each geothermal power plant is different.

Having reliable resources definitions and assessment are equally important for the geothermal energy sector as it is for the oil and gas industry (Bertani, 2005). However, it is extremely difficult to assess the resource accurately and reliably if comparing with solar and wind energies.

Table 5: unit size and the ability of modularization of renewable energies

	Unit size	Modularization	Scalability	Assessment
PV	1 W	High	High	Easy
Wind	1 KW	High	High	Easy
Hydro	1 KW	Middle	High	Easy-difficult
Geoth.	>70 KW	Low	High	difficult

According to the above data and analysis, the advantages and disadvantages of individual renewable energy are summarized in Table 6.

Table 6: Advantages and disadvantages of individual energies

Tech.	**Advantages**	**Disadvantages**
PV	Easy to assess resource	Low efficiency
	Easy to modularize	High cost
	Easy to install	Low capacity factor
	Low social impact	Not weather proof
	Easy to scale up	High land use
	Short construction period	
Wind	Low cost	Low capacity factor
	Easy to assess resource	Not weather proof
	Easy to modularize	High land use
	Easy to install	
	Low-medium social impact	
	Easy to scale up	
	Short construction period	
Hydro	High efficiency	High initial investment
	Low cost	Long construction time
	High capacity factor	Long payback time
Geoth	Medium-high efficiency	High initial investment
	High capacity factor	Long payback time
	Low to medium cost	Long construction time
	Weather proof	Tough to assess resource
		Tough to modularize

One can see that geothermal energy has many serious disadvantages in terms of current commercially available technologies although it has a lot of advantages.

The main disadvantage of PV and wind may be the capacity factor affected by weather, which causes serious stability problem and high risk to the electricity grid. As reported by Beckwith (2012): sometimes the wind will go from several thousand megawatts to zero in less than a minute. And gas plants cannot come on within a minute. Solar power plants may have similar problems. Geothermal power, on the other hand, is very stable.

Evans, et al. (2009) ranked the renewable energies in terms of sustainability (see Table 7) using data collected from extensive range of literature. The ranking revealed that wind power is the most sustainable, followed by hydropower, PV and then geothermal.

Table 7: Sustainability rankings (Evans, et al., 2009)

	PV	Wind	Hydro	Geothermal
Price	4	3	1	2
CO_2-equivalent	3	1	2	4
Availability	4	2	1	3
Efficiency	4	2	1	3
Land use	1	3	4	2
Water consumption	2	1	3	4
Social impacts	2	1	4	3
Total	20	13	16	21

Jacobson (2009) also ranked the renewable energies in terms of cleanness (see Table 8). Wind was also ranked No. 1 and geothermal was ranked No.3 in all of the 7 different types of renewable energies.

Table 8: Rankings of renewable energies (Jacobson, 2009; Evans, et al., 2009)

Ranking	By cleanness	By Sustainability
1	Wind	Wind
2	CSP	Hydro
3	Geothermal	PV
4	Tidal	Geothermal
5	PV	
6	Wave	
7	Hydro	

Jacobson (2009) pointed out: the use of wind, CSP, geothermal, tidal, PV, wave, and hydro to provide electricity will result in the greatest reductions in global warming and air pollution and provide the least damage among the energy options considered.

SOLUTIONS TO SPEED UP GEOTHERMAL POWER GROWTH

It is obvious that geothermal power has been lagged behind wind and solar in terms of both growth rate and installed capacity. As stated previously, geothermal power growth has only a few percent per year. The increase is more or less linear while wind and solar PV power exhibit fast-tracking growth with a clearly exponential tendency.

How do we speed up the growth of geothermal power? Many researchers have tried to answer this question. However there are no easy answers and solutions. Considering the present status and the literature review, some of the solutions and directions are suggested:

- New technology
- Co-produced geothermal power from oil and gas fields
- EGS

Discussion on the above possible ways and approaches to speed up geothermal power growth is addressed as follows.

New Technology

There have been many great technologies in the area of geothermal power generation. New technologies, however, are definitely required to speed up the growth of geothermal power. Why? It is because it has been tested and shown that current commercially available geothermal technologies can only yield a linear, instead of an exponential, and a very slow growth rate in the last four decades or so.

One of the new technologies that may make breakthrough is the technology to directly transfer heat to electricity, without going through mechanical function. Such a technology exists and has been utilized for a while in making use of waste heat. The core part of this technology is the thermoelectric generator or TEG (Thacher, 2007). TEG has almost all of the advantages of PVs. Plus, the lower limit temperature for generating electricity using TEG may be 30℃. With this advantage, much more geothermal resources might be used and much more power might be generated using TEG technology. Li, et al. (2013) has conducted some preliminary study on TEG.

Co-produced Geothermal Power from Oil and Gas Fields

There is a huge amount of geothermal resource associated with oil and gas reservoirs for power generation and other purpose (Li, et al., 2007; Erdlac et al., 2007; Johnson and Walker, 2010; Li, et al., 2012; Xin, et al., 2012). There are 164,076 oil and gas wells (2005 data) in China. 76,881 wells have been abandoned, about 32% of the total. These abandoned wells may be served as geothermal wells. The potential geothermal resource in the reservoirs holding these oil and gas wells is huge.

Erdlac, et al. (2007) reported that Texas has thousands of oil and gas wells that are sufficiently deep to reach temperatures of over 121°C and sometimes 204°C. In total there are 823,000 oil and gas wells in the United States. The possible electricity generation from the hot water, estimated by Erdlac, was about 47-75 billion MWh (equivalent to about 29-46 billion bbls of oil).

The main advantage of the co-produced geothermal power is the lower cost than that of EGS because the infrastructure, including wells, pipes, roads, and even grid, is already there.

EGS

One of the hot spots in geothermal industry in recent years was EGS since the publication of MIT report (Tester, et al., 2006). Many papers have been published in the area of EGS. It is known that EGS has a huge amount of resource. The EGS geothermal resource at a depth from 3.0 to 10.0 km in USA is equivalent to 2800 times of USA's 2005 annual total energy consumption if only 2% of the EGS resource can be recovered (Tester, et al., 2006). In China, 2% of the EGS resource at a depth of 3.0-10.0 km is about 5300 times of China's 2010 annual total energy consumption (Wang, et al., 2013). According to the above data, EGS has a great theoretical potential to speed up geothermal power growth. Unfortunately, it is obvious that EGS is presently still at the “proof of concept” stage, as pointed out by Rybach (2010).

CONCLUSIONS

According to the above review and analysis, the following preliminary remarks may be drawn:

(1) Geothermal power has been left behind wind and solar in terms of both growth rate and installed capacity. The main reasons may be high initial investment, long payback time and construction time, difficulty to assess resource and difficulty to modularize.

(2) Some of the solutions and directions to speed up geothermal growth may be: development and

utilization of new technologies such as TEG, co-produced geothermal power from oil/gas fields, and EGS. Currently EGS is still at the stage of "proof of concept".

(3) Geothermal power has the potential to grow exponentially in the future.

REFERENCES

Bertani, R.: "World geothermal power generation in the period 2001–2005," *Geothermics*, Volume 34, 2005, pages 651-690.

Beckwith, R.: "Switch: The New Documentary on Energy's Future," *JPT*, p. 52, November, 2012.

Chamorro, C. R., Mondéjar, M. E., Ramos, R., Segovia, J. J., Martín, M. C. and Villamañán, M. A.: "World geothermal power production status: Energy, environmental and economic study of high enthalpy technologies," *Energy*, V. 42, 2012, pages 10-18.

Erdlac, Jr., R.J., Armour, L., Lee, R., Snyder, S. Sorensen, M., Matteucci, M., and Horton, J.: "Ongoing Resource Assessment of Geothermal Energy from Sedimentary Basins in Texas," Proceedings of 32nd Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, January 22-24, 2007.

Evans, A., Strezov, V. and Evans, T.J.: "Assessment of sustainability indicators for renewable energy technologies," *Renewable and Sustainable Energy Reviews*, V. 13, 2009, pages 1082–1088.

Hong, W.: "The Rapid Increase of the World Solar Power," *Guangzhou Environmental Sciences*, Volume 1, 1999, page 16. [In Chinese]

Jacobson, M.: "A Plan for a Sustainable Future," Using Economics to Confront Climate Change, SIEPR Policy Forum Stanford University, October 30, 2009.

Johnson, L. A. and Walker, E. D.: "Oil Production Waste Stream, A Source of Electrical Power," Proceedings of 35th Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 1-3, 2010.

Kenny, R., Law, C. and Pearce, J. M.: "Towards real energy economics: Energy policy driven by life-cycle carbon emission," *Energy Policy*, Volume 38, 2010, pages 1969-1978.

Li, K., Zhang, L., Ma, Q., Liu, M., Ma, J., and Dong, F.: "Low Temperature Geothermal Resources at Huabei Oilfield, China," GRC Trans. V. 31 (2007).

Li, K., Wang, L., Mao, X., Liu, C. and Lu, J.: "Evaluation and Efficient Development of Geothermal Resource Associated with Oilfield," *Science & Technology Review*, Volume 32, 2012, pages 32-41. [In Chinese]

Li, K., Liu, C., and Chen, P.: "Direct Power Generation from Heat without Mechanical Function," Proceedings, 38th Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February11-13, 2013.

Li, M. and Wang, L.: "The Development and Utilization Trend of the Solar Energy Technology," *Energy Base Construction*, Volume 6, 2000, pages 12-14. [In Chinese]

Lucky, M.: "Global Hydropower Installed Capacity and Use Increase," Vital Signs Online, January 17, 2012. http://vitalsigns.worldwatch.org/vs-trend/global-hydropower-installed-capacity-and-use-increase

Majer, E., Baria, R. and Stark, M. (2008): Protocol for induced seismicity associated with enhanced geothermal systems. Report produced in Task D Annex I (9 April 2008), International Energy Agency-Geothermal Implementing Agreement.

Renewables 2012: Global Status Report, REN21 (Renewable Energy Policy Network for the 21st Century). Available at: www.ren21.net.

Rybach, L.: "Status and prospects of geothermal energy", Proceedings of World Geothermal Congress, 2010.

Stefansson, V.: "World Geothermal Assessment," presented at the Proceedings World Geothermal Congress 2005, Antalya, Turkey, Apr. 24-29.

Tester, J.W. et al. (2006) - The Future of Geothermal Energy – Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century, MIT-Massachusetts Institute of Technology, Cambridge, MA.

Thacher, E., Helenbrook, B., Karri, M. and Richter, C. J.: Testing of an automobile exhaust thermoelectric generator in a light truck. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, Vol. 221 (2007), p. 95-107.

Wang, G., Li, K., Wen, D., Lin, W., Lin, L., Liu, Z., Zhang, W., Ma, F. and Wang, W.: "Assessment of Geothermal Resources in China," Proceedings, 38th Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February11-13, 2013.

WEA (2000): World Energy Assessment Report: Energy and the Challenge of Sustainability. 500 p.

Xin, S., Liang, H., Hu, B., and Li, K.:"A 400 kW Geothermal Power Generator Using Co-Produced Fluids from Huabei Oilfield," GRC Trans. V. 36 (2012).